Implementation of an Optical Fiber Sensor System to Monitor the Response of Reinforced Concrete due to Formwork Removal

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***Abstract*—The movement of a section of a newly constructed reinforced 2-way suspended floor slab in the Department of Civil Engineering Science at the University of Johannesburg was monitored with an embedded optical fiber sensor (OFS) system during and after construction. The sensor system was used to monitor the strain in the structure before, during and after formwork removal. An OFS system was used due to its inherently distinct advantages such as its unobtrusiveness, lightweight and immunity to corrosion. This paper is concentrated on the findings of the results of these strain measurements with emphasis on the use of Fiber Bragg Gratings (FBG). Strain was measured over a 10 month period in a 5 m section of the suspended floor slab. Three periods during the 10 month period were observed. The first stage was showed 128 micro strain experienced by the structure. During the second stage the formwork was removed and large variations were monitored due to excessive external movement around the structure. The third stage indicated a 10 micro strain change. It was found that an OFS system can accurately measure the movement of reinforced concrete, thereby affording the design engineer to opportunity to monitor the structure during and after construction for large movements that can negatively affect the durability and the serviceability of the structure.**

Keywords—Embedded sensors, Continuous concrete monitoring, Fiber Bragg Gratings

I. Introduction

The rate of concrete hardening affects the formwork removal time. For example, the time required for removal of formwork in winter will be more than the time required during the summer season[1]. Special construction designs are required from engineers for formwork removal time of flexural members such as beams and slabs, as these members are subjected to self-load as well as a live load during early ages of construction[2]. Premature removal of formwork or stripping will cause larger non-recoverable long term movement in concrete, due to the concrete still having low early age strength. Furthermore, long term deflections are increased[3], thereby adversely affect the long term serviceability and durability of the concrete structure[4].

Commonly used conventional movement monitoring techniques (e.g. electrical and mechanical strain gauges) have only limited number of tests that can be done physically, where human error can affect the accuracy of the measurement[5]. Thus, there is a need for new methods to monitor movement in concrete[6]. The application of optical fiber sensors could be an acceptable alternative to the conventional methods currently used in the South African construction industry[6].

Previously, several studies have been performed with the goal of improving the knowledge of concrete movement and developed new techniques associated with the application of optical fiber sensors in concrete structures[6]. FBGs can be embedded directly into the concrete to provide real-time information with regards to movement and internal temperature throughout the concrete structure’s design life[7].

Fiber optic sensors offer a wide range of features that are advantageous in the construction industry when compare to conventional strain measuring devices, the new idea of smart structures has driven the development of optical fiber sensors [8],[9].The new technology, driven as smart structures, will result in an improvement of safety issues and avoidance of inadequately designed structures[8]. Fibre optic sensors can sense real-time strain in a structure as well as precise localization and quantification of the strain measured in a structure [4].

II. Background

A. Optical fibre sensors

There are many sensing applications that are available using conventional strain sensors. These include sensors such as: electrical strain gauges, Piezoresistors, extensometer and string potentiometers as well as noncontact sensors which use Digital Image Correlation[10]. However there are disadvantages to using these traditional methods.

The biggest drawback of using electrical sensors, is that each sensor requires a pair of wires. This poses a problem when measuring strain over a distributed range with many sensing points, as the amount of wires increase drastically and may pose a threat to the structural health of a civil structure.

Another drawback of using traditional methods are, that they don’t allow for real time continuous measurement over an extended period of time, making it difficult to predict the actual performance of a structure.

Although traditional methods are fairly easy to implement, without the need for complex devices, the drawbacks of these methods are critical. Thus, a convenient system has been designed and built to monitor the micro strain of a structure. This project utilized optical fiber components, incorporating Bragg grating (FBG) sensors.

Previously, there have been a lot of optical fiber sensor based monitoring systems that have been developed for continuous, real-time measurement for a vast number of engineering structures. Most notably by Kerrouche et al. who measured the strain on a rail bridge until failure [11] as well as K.Kesavan et al. who monitored corrosion of reinforced concrete [12].

B. Concrete strain or movement

Concrete structures experience movement throughout their life-cycle, in both the fresh and hardened states [2]. The movement is characterised as shrinkage or expansion of the concrete. Movement significant influence overall performance of concrete structures[2]. The fundamental problem with movement is that it may lead to undesirable stress development in the concrete structure, which can lead to excessive deflection and cracking within the concrete structure[2], leading to a reduction in strength, durability and the serviceability of the structure[5].

Concrete movement is the change in micro strain, described as shrinkage or swelling respectively, as mapped in Figure 1 [13]. There are different types of shrinkage. Chemical or autogenous shrinkage is the shrinkage caused by chemical reactions occurring in the concrete, and is related to the degree of hydration of the binder in concrete[9]. Drying shrinkage is the reduction in volume caused principally by the loss of water during the drying process[14]. Concrete shrinkage strain which is usually considered to be the sum of drying and chemical shrinkage components continues with time at a decreasing rate[6].

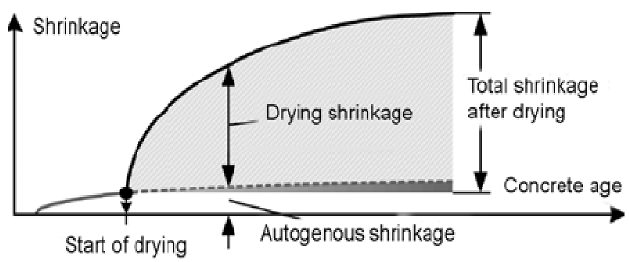

Fig.1. Shrinkage strain components in normal concrete [13].

The greatest movement occurs during the first drying shrinkage when a large part of the shrinkage cannot be recovered if the concrete is later re-wetted as shown in Fig.1[7]. On subsequent wetting, if the concrete experience excessive construction loads at an early age, it can cause higher creep deflection and may cause the concrete to experience movement, more than anticipated[15]. These excessive construction loads are due to inadequate shored or restored levels, early formwork removal, or both[3]. Fig.1 illustrated how concrete moves as it ages.

III. IMPLEMENTATION

Due to the many drawbacks of electrical and mechanical sensing technologies, a temperature and strain monitoring system has been developed using an optical fiber sensor configuration. The main reason for this decision was the relative ease in which the sensors can be embedded and the ability to implement the sensors into a single optical fibre line. There are various fiber optic sensing methods that are available, such as Fabry-Perot and fibre Bragg grating sensors. For this project, FBG sensors were selected as they are relatively easy to fabricate and interrogate.[16]

Although there has been major improvements in the field of optical fiber, it has always been a challenge to integrate components such as mirrors, filters and partial reflectors into an optical fiber cable. However, this changed with the ability to alter the refractive index of the core by means of irradiating the fiber with and ultra violet laser source. The photosensitivity of optical fiber allows for the fabrication of periodic phase structure directly into the core of the fiber. The fiber Bragg grating can perform functions such as reflections and filtering in a low loss, high efficient manner[17]. The Bragg grating sensor consists of a segment of an optical fiber in which a periodic modulation of the core refractive index has been formed by means of exposure to an interference pattern of intense ultra-violet light source [18].

Fig.2 illustrates the basic operational principle of a fibre Bragg grating (FBG). A broad-spectrum (λ_{Broad}) pulse of light is launched into the fiber. When the pulse of light reaches the grating, it reflects at the wavelength it was designed to be reflected at [Bragg Wavelength (λ_B)]. λ_B is also known as the optical back-reflected spectrum and comprises of a very narrow reflected wavelenght. Once this back-reflection is reflected, the rest of the pulse passes through the filter unaffected. This is seen in Fig. 2 where the pulse traveling through the input is a broad spectrum but after the grating, the broad spectrum minus the reflected signal is transmitted. The reflected wavelength, λ_B is detected.

When the Bragg grating is fabricated, it is done at a constant temperature, humidity and without any strain applied to the cable. This means that the grating will not change under ideal conditions and will therefore only reflect its designed wavelength. If there is a temperature change or applied strain, the grating physically expands or contracts (temperature change) or bends (applied strain) causing a different wavelength to be reflected. The reflected wavelength (λ_B) is related to the printed grating by (1) [19], where n_{eff} is the refractive index of the periodically modified fiber core and Λ is the spacing between the modulated refractive index change.

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

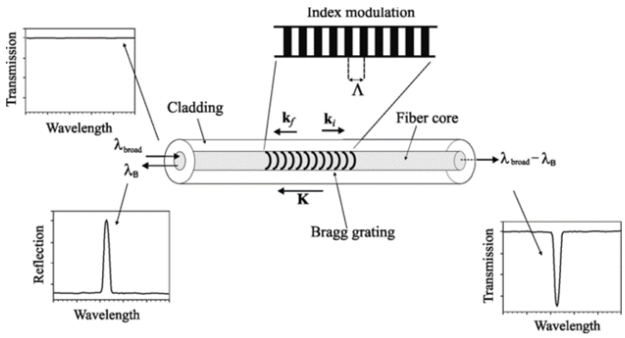

Fig.2. Representation of FBG [17]

Because the reflected Bragg wavelength is a function of spacing between the modulated refractive index change, FBGs can be manufactured with various Bragg wavelengths which allows various FBGs to reflect unique wavelengths of light.

Change in temperature and strain both effect the refractive index (n) and grating period (Λ) of an FBG. As a result, there is a shift in the reflected wavelength that can be approximated by (2) where $\Delta\lambda$ is the shift in wavelength in nm and λ_0 is the initial wavelength in nm [17].

$$\frac{\Delta\lambda}{\lambda_0} = [\varepsilon(1 - P_e)] + [\Delta T(\alpha_\Lambda + \alpha_n)] \qquad (2)$$

The first part of the expression, $[\varepsilon(1 - P_e)]$, describes the impact of strain on the wavelength shift, where P_e is the strain optic coefficient and ε is the strain experienced by the grating. The second expression, $[\Delta T(\alpha_\Lambda + \alpha_n)]$, describes the impact of temperature on the wavelength shift. α_Λ is the expansion coefficient and α_n is the thermo-optic coefficient[17].

Because FBGs responds to both strain and temperature, when measuring strain, temperature compensation must be performed. This is done by a method called “Temperature Compensation”[20]. A separate sensor is imbedded to measure the only temperature (no strain is applied to the temperature measuring FBG) and its change in reflected wavelength ($\Delta\lambda$) reading is subtracted from the strain sensor wavelength change in wavelength values. This forces the second term of (2) to be zero and only the first term is considered.

To simplify the build process, the system was broken down into four sub-systems. Namely: The FBG Sensor, the Optical Cable, the Interrogator and finally the PC analyzer. For this system, an HBM interrogator was used to supply the system with a broad light spectrum as well as receive, interrogate and analyse the reflected wavelength. The optical fiber cabling that was chosen was a 48 strand cable. And the FBG sensors were fabricated using an Nd:YAG laser operating at 266 nm and a phase mask technique as illustrated in Fig.3.

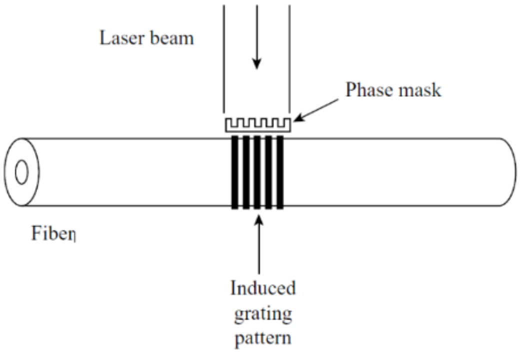

Fig.3. Phase Mask Fabrication Technique *[21]*

IV. EXPERIMENTAL SETUP

Two optical fibers lines, the first consisted of five strain FBG sensors, the second line consisted of a single temperature FBG sensor. Both lines were secured to the steel reinforcement of the concrete element before the fresh concrete was placed and is illustrated in Fig.4. Fig.5 illustrates the placement of the fiber cable and fiber sensor in the suspended 2-way floor slab.

Fig.4. Optical fiber lines secured to reinforcement.

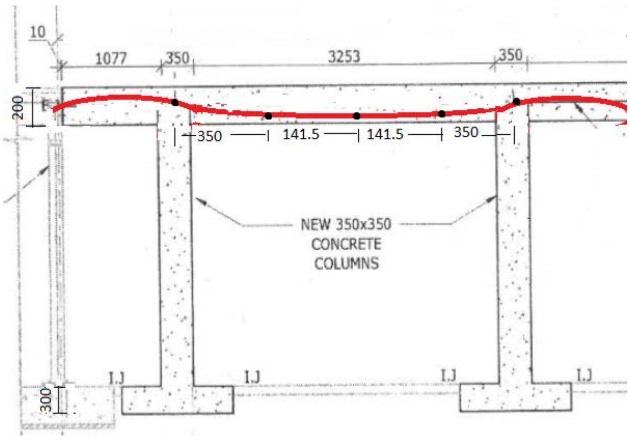

Fig 5, Lay-out of the two optical fiber lines

The concrete was placed on the 7th of August 2018, while the measurements only started on the 17th of August 2018. Data logging occurred using a commercial FBG interrogator (HBM FS22SI BraggMeter). Measurements were taken during the following periods:

- Stage 1: Before support removal – 17th August 2018 for 35 hours at 1 hour intervals
- Stage 2: Support removal – 21st August 2018 for 54 hours at 1 hour intervals
- Stage 3: Latter age monitoring – 28th May 2019 for 20 hours at 1 hour intervals

V. RESULTS AND DISCUSION

As can be seen from Fig 6 all five FBG's measured an increase in the micro strain during Stage 1. Even though the measurements were not taken directly after final set, it can still be seen from Fig 6 that there is an increase in the micro strain experienced by the concrete element to the amount of 128 micro strain during the 35 hours of measurement. In addition, all five FBG sensors measured very similar values, and indicate a very similar shape. As time elapsed the rate of increase in the micro strain slowed down. The trend that was exhibited by all five the FBG's corresponds to the trend indicated in Fig 1. The strain in the element may be attributed to autogenous shrinkage. There will be very limited shrinkage due to the drying of concrete. This is due to the fact that the bottom and sides of the concrete was still in the steel shutters that covers the bottom and sides of the concrete. The top part of the concrete was sprayed with curing compound, effectively sealing the surface of the concrete, thereby stopping evaporation of moisture out of the concrete.

During Stage 2 it can be seen, from Fig 6, that there was large fluctuations in the micro strain experienced by all five the FBG sensors. Over the 54 hours, there was fluctuations of between 665 and 929 micro strain in the sensors. All five the strain sensors follow the same trend in their fluctuations. This can be attributed to the fact that during the removal of part of the support system from the soffit level of the 2-way suspended floor slab, the concrete experienced small upwards and downwards movement, causing the micro strain to fluctuate. It must be remembered that the concrete is still gaining strength, and has not reached its specified compressive strength as yet. These movements may induce small cracks in the concrete, negatively affecting the durability and serviceability of the concrete element. These fluctuations in micro strain, is not indicated in Fig 1.

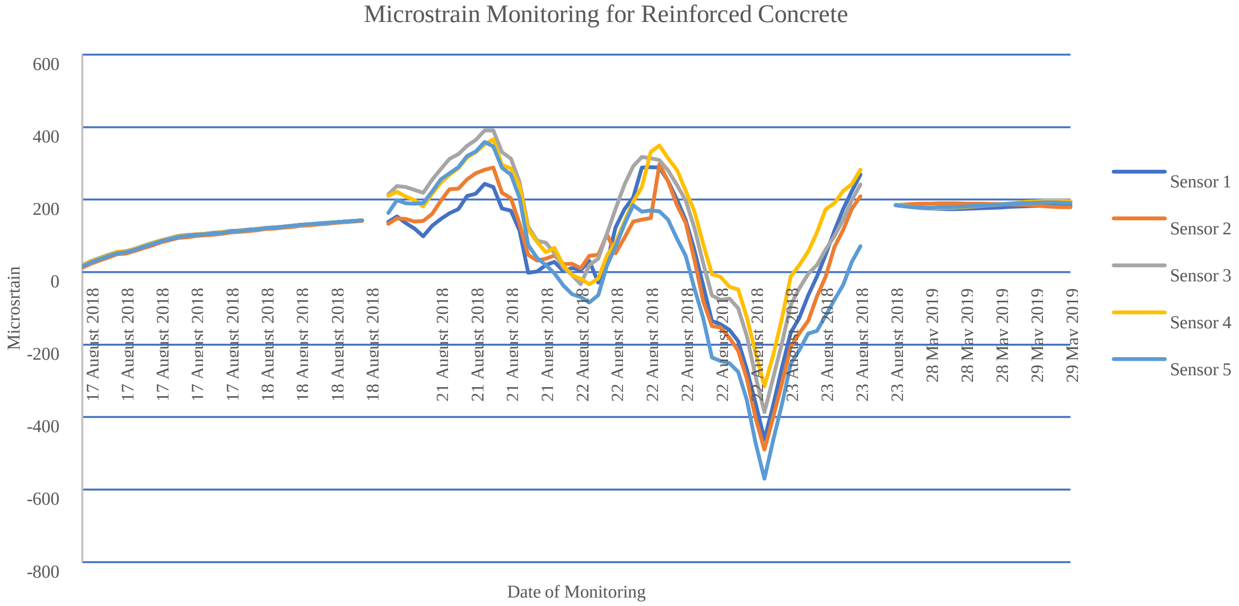

Fig.6. Results of all three stages of strain monitoring

During Stage 3 it can be seen from Fig 6 that there is a very small increase, to the amount of around 10 micro strain, measured by the FBG sensors during the 20 hours. All five FBG sensors exhibited the same shape. Again, as with Stage 1 of the measurements, it can be seen that the general shape has continued on the trend of autogenous shrinkage that is indicated in Fig 1. There is no big increase in the micro strain that is shown in Figure 1 due to drying shrinkage. The reasons for this is that the concrete element is in an extension of a floor slab that is located within an exciting structure. Therefore, there is no direct sunlight, nor any wind that can evaporate the moisture from the concrete. In addition, the top surface of the concrete has been carpeted over, thus effectively sealing it off from the environment. All of these factors leads to very little evaporation of moisture from within the hardened concrete.

VI. CONCLUSION

A section of a newly constructed suspended 2-way floor slab and beam was incrementally monitored over a period of just over 10 months. Strain and temperature FBG sensors, installed in two separate optical fiber lines over a 5 meter section, were embedded in the suspended concrete element. The sensors measured 128 micro strain during the first 35 hour period and followed the autogenous trend as illustrated in Fig.1. The sensors also showed a large variation in the strain measurement when the support structure was removed. This indicates that this optical sensor system would be also able to monitor large structural movement that may be affect the structural serviceability and deflections.

From the research it can be seen that the use of optical fiber sensors are a viable method to measure movement of concrete during construction, and has the potential to be used in the long term monitoring of movement and temperature in concrete structures. By monitoring the movement of reinforced concrete structures, it should be possible to extend the serviceability of the structure.

VII. FUTURE WORK

Although system measures accurately and efficiently, the system could be altered to measure a wider range of structural properties, such as moisture content, corrosion cracking and/or pressure. The system could be designed and implemented to smart structures to monitor, detect and warn users of potential hazards in real time.

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